Physics Letters B 682 (2010) 337–341

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Cosmology with long-lived charged massive particles

Kazunori Kohri [a,b], Tomo Takahashi [c,*]

[a] Department of Physics, Tohoku University, Sendai 980-8578, Japan
[b] Physics Department, Lancaster University, Lancaster LA1 4YB, UK
[c] Department of Physics, Saga University, Saga 840-8502, Japan

ARTICLE INFO

Article history:
Received 5 October 2009
Received in revised form 19 November 2009
Accepted 19 November 2009
Available online 27 November 2009
Editor: T. Yanagida

ABSTRACT

We investigate the evolution of the bound state of negatively charged massive particles (CHAMPs) with light elements and discuss its cosmological consequences and the constraint. By numerically solving the Boltzmann equation, we study the time evolutions of such bound states. Since most of negative CHAMPs are captured by ^{4}He, its bound state is positively charged and couples with the electromagnetic plasma. When charged particles constitute a dominant non-relativistic component, density fluctuations of matter cannot grow due to the acoustic damping. This results in the suppression of matter power spectrum from which a severe constraint can be obtained. By arguing constraints from other aspects of cosmology, we show that the constraint from large scale structure gives most stringent one in some representative cases.

1. Introduction

Long-lived charged massive particles (CHAMPs) can exist in various extensions of the standard model of particle physics such as supersymmetry (SUSY). One of such example is a slepton, a superpartner of leptons, which can be stable if it is the lightest supersymmetric particle (LSP) and R-parity is conserved. However, the abundance of such stable charged massive particles would be severely constrained [1], in particular, from experiments of the deep sea water [2–7]. Although there might have been a mechanism to prevent them being captured into the Earth [8] and in such a case the constraints may not be applicable, a scenario with stable CHAMPs would generally not be viable. However, in some other scenarios, CHAMPs are unstable, and they can constitute a dominant component of non-relativistic particles in the early Universe. For example, when the gravitino is the LSP, which can be easily realized in gauge-mediated SUSY breaking models [9–11], the next lightest supersymmetric particles (NLSP) may be CHAMPs, and they can be long-lived. Although such unstable CHAMPs can evade the constraint from the sea water, they affect other aspects of cosmology. It has been rigorously investigated that the decay of such massive particles would destroy light elements synthesized by big bang nucleosynthesis (BBN), from which we obtain constraints on the properties of CHAMPs such as the decay rate and its abundance [12–23]. Although the considerations of the decay also applies to neutral massive particles, there is another important effect on BBN which is specific to the charged particles: the bound-state effect. Negative CHAMPs can form a bound state with positively charged light elements, which affects the BBN reaction rates and their abundances [24–40]. In fact, as will be shown later, most negative CHAMPs (referred to as X^-) are captured by ^{4}He, a double-positively charged element. If this bound state (^{4}HeX^-) is stable for some time in the course of the history of the universe, it would also affect other aspects of cosmology in addition to BBN such as large scale structure. Thus a detailed investigation of how the bound states are formed and evolve would be important and interesting, which is one of the main topics in this Letter.

When a particle possesses an electric charge before recombination, it is tightly coupled with the plasma of electrons and photons. Thus such charged particles, which are supposed to be the bound state (^{4}HeX^-) here, can also participate in the acoustic oscillations. When the bound state of negative CHAMPs constitutes a dominant component of non-relativistic particles, fluctuations of (non-relativistic) matter cannot grow due to the "acoustic damping" caused by the acoustic oscillations, which is different from the case with a standard neutral cold-dark matter (CDM) model. This results in the suppression of the matter power spectrum at some scales [41–43]. Thus the bound state (^{4}HeX^-) should have a significant effect on large scale structure, and the consideration of this issue can place a unique bound on the properties of (negative) CHAMPs, which is another topic we are going to focus in this Letter.

The organization of this Letter is as follows. In the next section, we first carefully investigate the evolution of the bound states of X^- with some light elements by numerically solving the Boltzmann equation. Then we discuss the effect of the (charged) bound

* Corresponding author.
E-mail address: tomot@cc.saga-u.ac.jp (T. Takahashi).

0370-2693
doi:10.1016/j.physletb.2009.11.051

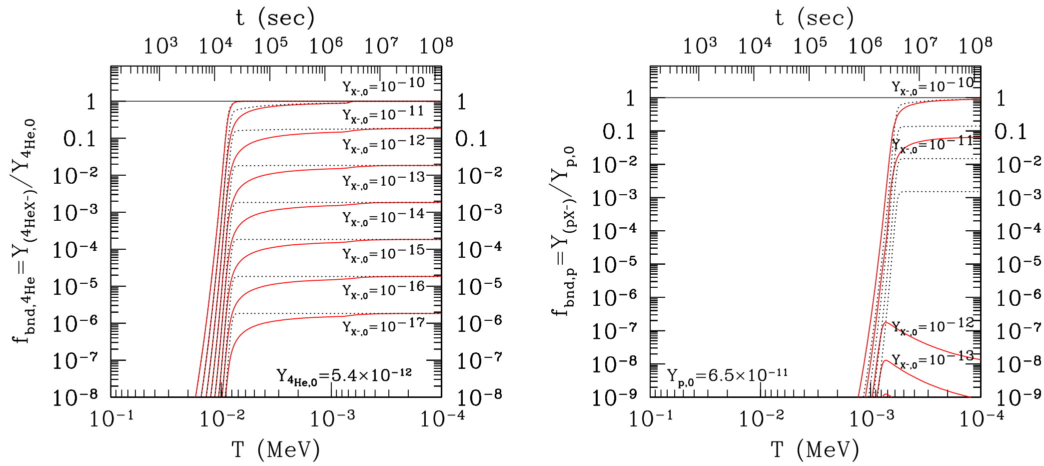

Fig. 1. Time evolution of $f_{\mathrm{bnd},N_i} \equiv Y_{(N_iX^-)}/Y_{N_i,0}$ with $N_i = {}^4\mathrm{He}$ (left) and $N_i = p$ (right), where $Y_{N_i,0}$ and $Y_{X^-,0}$ are the initial values of Y_{N_i} and Y_{X^-}, respectively. The dashed lines denote solutions of Saha's equation. In these figures we assumed that X^- is stable.

state on large scale structure and the damping of matter power spectrum. In Section 4, we discuss the constraint on the property of CHAMPs from large scale structure and some other aspects such as BBN and the CMB spectrum. The final section is devoted to the summary of this Letter.

Unless otherwise stated, throughout this Letter n_i, m_i and Y_i denote the number density, the mass and the yield variable ($\equiv n_i/s$ with s the entropy density) of a particle "i", respectively.

2. Evolution of the bound state

We are interested in the bound-state formation of X^- with a light element, which occurs after the cosmic temperature becomes lower than 30 keV. Until that time, most of the standard BBN processes should have almost been finished. Under this circumstance, the Boltzmann equations for the time-evolution of the number density of bound states (N_iX^-), denoted as $n_{(N_iX^-)}$, with $N_i = p$ and ^{4}He are expressed by

$$\begin{aligned}\frac{dn_{(^4\mathrm{He}X^-)}}{dt} &= -3Hn_{(^4\mathrm{He}X^-)} - \Gamma_X n_{(^4\mathrm{He}X^-)} \\ &\quad + \langle\sigma_{\mathrm{bnd},^4\mathrm{He}}v\rangle\Bigg[(n_{^4\mathrm{He}} - n_{(^4\mathrm{He}X^-)})n_{X^-} \\ &\quad - \left(\frac{m_{^4\mathrm{He}}m_X T}{2\pi m_{(^4\mathrm{He}X^-)}}\right)^{3/2} e^{-E_{b^4\mathrm{He}}/T} n_{(^4\mathrm{He}X^-)}\Bigg] \\ &\quad + \langle\sigma_{\mathrm{ex}}v\rangle(n_{^4\mathrm{He}} - n_{(^4\mathrm{He}X^-)})n_{(pX^-)}, \qquad (1)\end{aligned}$$

$$\begin{aligned}\frac{dn_{(pX^-)}}{dt} &= -3Hn_{(pX^-)} - \Gamma_X n_{(pX^-)} \\ &\quad + \langle\sigma_{\mathrm{bnd},p}v\rangle\Bigg[(n_p - n_{(pX^-)})n_{X^-} \\ &\quad - \left(\frac{m_p m_X T}{2\pi m_{(pX^-)}}\right)^{3/2} e^{-E_{bp}/T} n_{(pX^-)}\Bigg] \\ &\quad - \langle\sigma_{\mathrm{ex}}v\rangle(n_{^4\mathrm{He}} - n_{(^4\mathrm{He}X^-)})n_{(pX^-)}, \qquad (2)\end{aligned}$$

where n_{X^-} is the number density of free X^-, Γ_X is the decay width of X, $E_{b^4\mathrm{He}} \simeq 337.33$ keV and $E_{bp} \simeq 24.97$ keV are the binding energies of $(^4\mathrm{He}X^-)$ and (pX^-) [31], and $n_{^4\mathrm{He}}$ and n_p are the number densities of ^{4}He and proton including both free and bound-states. The masses of the bound states are given by $m_{(^4\mathrm{He}X^-)} = m_{^4\mathrm{He}} + m_X - E_{b^4\mathrm{He}}$ and $m_{(pX^-)} = m_p + m_X - E_{bp}$, respectively. The thermally-averaged recombination cross sections $\langle\sigma_{\mathrm{bnd},^4\mathrm{He}}v\rangle$ and $\langle\sigma_{\mathrm{bnd},p}v\rangle$ for the ^{4}He and p bound-states formation are given by [27]

$$\langle\sigma_{\mathrm{bnd},^4\mathrm{He}}v\rangle \simeq 98.46\frac{\alpha E_{b^4\mathrm{He}}}{m^2_{^4\mathrm{He}}\sqrt{m_{^4\mathrm{He}}T}}, \qquad (3)$$

$$\langle\sigma_{\mathrm{bnd},p}v\rangle \simeq 24.62\frac{\alpha E_{bp}}{m_p^2\sqrt{m_p T}}, \qquad (4)$$

where T is the cosmic temperature, and α is the fine structure constant.

The terms in the third lines of the right-hand side of Eqs. (1) and (2) represent a charge-exchange reaction,

$$(pX^-) + {}^4\mathrm{He} \to ({}^4\mathrm{He}X^-) + p, \qquad (5)$$

with its thermally-averaged cross section being denoted as $\langle\sigma_{\mathrm{ex}}v\rangle$. This process is effective just after (pX^-) has been formed. Recently it has been reported that a rate of this charge-exchange reaction is more rapid than the Hubble expansion rate [44] at the formation epoch of (pX^-) which is approximately given by

$$\frac{\langle\sigma v\rangle n_{^4\mathrm{He,free}}}{H} \sim 2.6\times10^4\left(\frac{T}{0.5\ \mathrm{keV}}\right), \qquad (6)$$

where we took the yield variable of free ^{4}He to be $Y_{^4\mathrm{He,free}} = 5.4\times10^{-12}$. This means that the produced (pX^-) is immediately destroyed, and rather X^- is included into $(^4\mathrm{He}X^-)$ after the destruction.

In Fig. 1, we plot the time evolution of $f_{\mathrm{bnd},N_i} \equiv Y_{(N_iX^-)}/Y_{N_i,0}$ with $N_i = {}^4\mathrm{He}$ (left) and $N_i = p$ (right), where $Y_{N_i,0}$ and $Y_{X^-,0}$ are the initial values of Y_{N_i} and Y_{X^-}, respectively. Here the initial value of Y_{N_i} means the one after N_i's standard BBN processes have finished and well before its bound-state formation starts. $Y_{X^-,0}$ is the initial value of Y_{X^-} well before X^- decays, and/or its bound-state is formed. The dashed lines denote solutions of Saha's equation,[1]

$$Y_{(N_iX^-)} = \left(\frac{m_{^4\mathrm{He}}m_X T}{2\pi m_{(N_iX^-)}}\right)^{-3/2}$$

[1] Note that Saha's equation represents the equilibrium between X^- and N_i and assumes only one component of N_i. Therefore, there should be deviations from this solution when we consider two components of N_i ($= p$ and ^{4}He). However because the dashed lines still give us useful information to understand behaviors of the numerical solutions, we also plot them in Figs. 1 and 2.

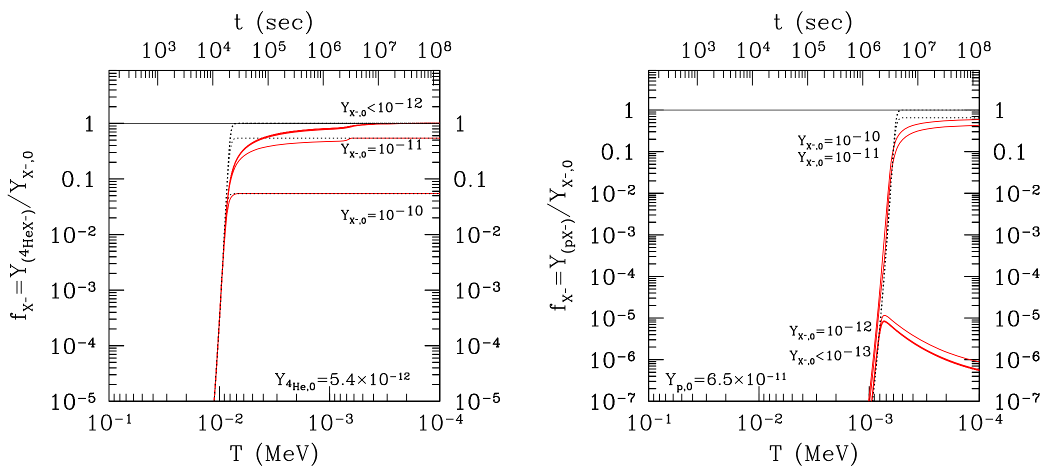

Fig. 2. Time evolution of $f_{X,N_i} \equiv Y_{(N_i X^-)}/Y_{X^-,0}$ with $N_i = {}^4\mathrm{He}$ (left) and $N_i = p$ (right). The meanings of the labels and lines are the same as those in Fig. 1.

$$\times\, e^{E_{bi}/T} s(Y_{N_i} - Y_{(N_i X^-)})(Y_{X^-} - Y_{(N_i X^-)}). \tag{7}$$

From the figure, we can see that the bound states form at around $T \sim 10$ keV and 1 keV for $({}^4\mathrm{He}X^-)$ and (pX^-), respectively.

The time-evolution of the $({}^4\mathrm{He}X^-)$ formation excellently agrees with the solution of the Saha's equation. On the other hand, deviations from the Saha's equation can be seen in case of (pX^-). The behavior of the time-evolution of (pX^-) seen in Fig. 1 (right) can be easily understood as follows. If $Y_{X^-,0} \gg Y_{^4\mathrm{He},0}$, sufficient amounts of free X^- exist, independently of the detail of $({}^4\mathrm{He}X^-)$ formation, and the abundance of (pX^-) approximately follows the solution of Saha's equation. On the other hand, if $Y_{X^-,0} \ll Y_{^4\mathrm{He},0}$, the abundance of (pX^-) should deviate from Saha's equation. Furthermore, the charge-exchange reaction becomes important when $\langle\sigma_{\mathrm{bnd},p} v\rangle Y_{X^-} Y_p \sim \langle\sigma_{\mathrm{ex}} v\rangle Y_{(pX^-)} Y_{^4\mathrm{He}}$. Then the formation of (pX^-) is balanced between the production and the destruction processes, and the abundance becomes approximately the order of $Y_{(pX^-)} \sim 0.5 \times 10^{-5} Y_{X^-,0}(T_c/\mathrm{keV})^{-1/2}$. Thus the production of (pX^-) stops at around $T_c \sim 0.6$ keV for $Y_{X^-,0} < 10^{-12}$ seen in Fig. 1 (right). This feature is consistent with Fig. 2.7 in Ref. [45] and what was stated in Ref. [44]. The reason why X^-s are included mainly into ^{4}He is that the number density of X^- is much smaller than that of electron, which is completely different from the case of the standard recombination of electron.

On the other hand, in Fig. 2 we plot the time evolution of $f_{X,N_i} \equiv Y_{(N_i X^-)}/Y_{X^-,0}$ with $N_i = {}^4\mathrm{He}$ (left) and $N_i = p$ (right). Similarly to Fig. 1 the dashed lines show the result of Saha's equation. From Fig. 2 we see that most of X^- are captured into the bound state with ^{4}He if $Y_{X^-,0}$ is smaller than 10^{-12}. This means that (pX^-) disappears immediately after its formation for $Y_{X^-,0} \lesssim 10^{-12}$. Then we find that almost all X^-s are captured by ^{4}He, and form the bound state $({}^4\mathrm{He}X^-)$. Because the abundances of other singly-charged nuclei such as deuterium and tritium, are much smaller than that of proton, we can omit contributions from deuterium and tritium. This result tells us that the bound states of X^- cannot be neutralized even after (pX^-) could have been formed.

The fact that the total electric charges of the dominant non-relativistic components cannot be shielded has a strong impact on the structure formation. We discuss this issue in the next section.

3. Effect on large scale structure

In this section, we discuss the effect of the charged bound state on large scale structure. In fact, the discussion below also applies to charged (massive) particles themselves when they constitute a dominant non-relativistic component. Thus in the following, we use "CHAMPs" to indicate both the free CHAMPs and the bound states of CHAMPs with light elements which have a net electric charge. When there exist long-lived CHAMPs, they couple with photon–baryon fluid, thus matter density fluctuations oscillate under the scales which enters the horizon before CHAMPs decay. Thus fluctuations of matter cannot grow, then the matter power spectrum is suppressed on corresponding scales, which is called "acoustic damping" in literature.

An explicit calculation has been done on how the matter power spectrum is suppressed in [41,42]. To obtain the constraint on the decay rate rigorously, we need to compare the matter power spectrum with observational data. However, when CHAMPs are dominant component of non-relativistic matter, the matter spectrum is abruptly suppressed at the damping scale. Thus the evaluation of the damping scale would be enough to obtain the constraint on CHAMPs. Hence in the following, we simply make an estimate of the acoustic damping scale as a function of the decay rate.

The scale under which matter power spectrum is suppressed, which we denote k_X in the following, can be estimated as follows. For fluctuations of the scale which enters the horizon before CHAMPs decay ($t < \tau_X$ where τ_X is the lifetime of CHAMPs), they are damped by the acoustic oscillation. On the other hand, fluctuations of the scale which enters the horizon when $t > \tau_X$, in other words, they can be assumed to be usual neutral dark matter, fluctuations of such scales grow with time as in the standard case.[2] Since the horizon-crossing occurs when $k = aH$ with H being the Hubble parameter, the characteristic scale k_X under which the matter power spectrum is suppressed is defined by

$$k_X \equiv aH|_{t=\tau_X}. \tag{8}$$

We assume that the CHAMPs decay during radiation-dominated (RD) epoch. Then H is related to the cosmic time as $H = 1/2t$. On the other hand, during RD, H can be also written as $H^2 \simeq \rho_{\mathrm{rad}}/3M_{\mathrm{pl}}^2 = H_0^2 \Omega_{\mathrm{rad}} a^{-4}$. Putting these together, we obtain the characteristic scale k_X as

$$k_X = \sqrt{\frac{H_0}{2\tau_X}}\,\Omega_{\mathrm{rad}}^{1/4}. \tag{9}$$

[2] Here we do not consider free-streaming of nonthermally-produced dark-matter particles because it depends on the kinetic energy of the dark matter just after its production by the X^- decay, which would be highly model-dependent. To obtain a conservative constraint, we neglect this effect here.

To make some rough estimate, we recall that $\Omega_{rad}h^2 \simeq 4.15 \times 10^{-5}$ and $H_0 \sim h/(3 \times 10^{17})$ s, we obtain

$$k_X \simeq 10^4 \sqrt{\frac{s}{\tau_X}}\ \mathrm{Mpc}^{-1}. \tag{10}$$

For example, when $\tau_X \sim 1$ s, the corresponding damping scale is $k_X^{-1} \sim 0.1$ kpc. For $\tau_X \sim 10^6$ s, the damping scale becomes $k_X^{-1} \sim 10^2$ kpc, which is the order of the galaxy scale. Here it should be mentioned that the damping scale down to $k_X^{-1} \sim 1$ kpc can be probed with future observations of QSO-galaxy strong lens system [43]. Thus the constraints from large scale structure would be much more stringent and such future observations give us a lot of information on CHAMPs.

4. Constraints on CHAMPs

Now we discuss the constraint on the abundance and the decay rate of CHAMPs from some cosmological observations, paying particular attention to that from large scale structure. We show the constraint on the Y_{X^-} vs. τ_X plane, where Y_{X^-} is the yield variable of X^- which is the number density of X^- to the entropy density ratio. In the following, we assume that the energy density of CHAMPs is fixed to give the present dark matter density if they are stable. (I.e., the energy density of CHAMPs before the decay is fixed by this requirement.) Thus the yield variable and the mass are related as

$$Y_{X^-} \simeq 4 \times 10^{-12} \Omega_{DM} h^2 \left(\frac{10^3\ \mathrm{GeV}}{m_{X^-}} \right). \tag{11}$$

In Fig. 3, we draw the acoustic damping scales $k_X^{-1} = 1$ Mpc, 100 kpc, 10 kpc, 1 kpc and 0.1 kpc by the vertical long-dashed lines. If we confirm structures larger than a scale, we can exclude the right region of the corresponding line. Here it should be noted that unstable CHAMPs can erase the structure of small scales, and thus can solve some problems regarding the discrepancies between observations [46,47] and predictions of N-body simulation in ΛCDM model [48–52].[3]

Another important constraint comes from the overproduction of ^{6}Li by the Catalyzed BBN through $(^4\mathrm{He}X^-) + \mathrm{D} \to {}^6\mathrm{Li} + X^-$ induced by the formation of $(^4\mathrm{He}X^-)$ [26]. Observational fraction of $^6\mathrm{Li}/^7\mathrm{Li}$ gives a upper bound on Y_{X^-} [26,30–34]. Notice that the constraint from CBBN does not depend on the CHAMP mass. The upper bound on Y_{X^-} for $\tau_X > 10^6$ sec is $Y_{X^-} < 2 \times 10^{-15}$. Thus, requiring the abundance of CHAMPs gives the present dark matter density if they are stable, the constraint from large scale structure becomes more relevant than that from CBBN for $m_X \gtrsim 10^6$ GeV.

For reference, we also show other possible constraints placed on Y_{X^-} and τ_X from the photodissociation of BBN [17] and CMB y- and μ-distortion of CMB spectrum [56] with the mass of CHAMPs being fixed independent of the relation of Eq. (11). Since the way of fixing the mass is different from that in other constraints, these constraints should be interpreted with some care in the figure. Here we assumed that X^- emits electromagnetic particles and take some representative values for the energy injected from the

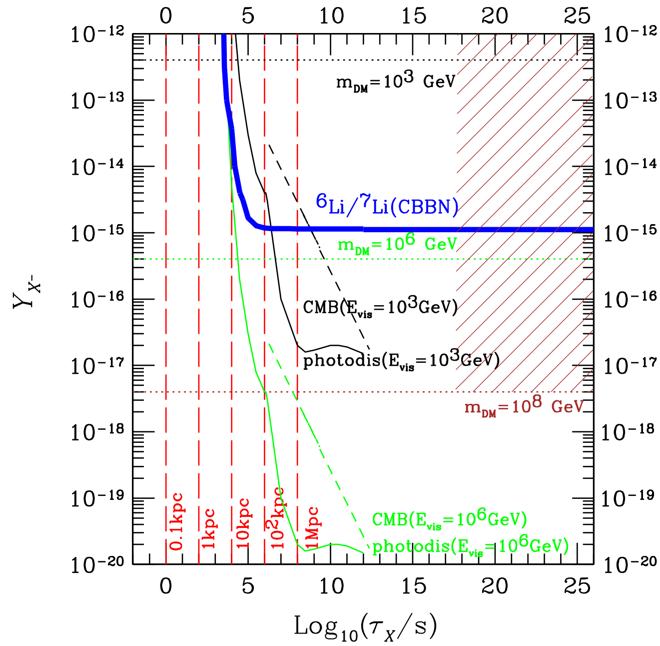

Fig. 3. Constraints on the yield variable and decay rate of negative CHAMPs. The energy density of CHAMPs is fixed to give the present dark matter density if they are stable and then the mass is also fixed by this requirement. The corresponding masses are given by the horizontal dotted lines with the label near the lines (see also Eq. (11)). The right side of vertical long-dashed line is excluded by the requirements that 0.1 kpc, 1 kpc, 10 kpc, 100 kpc, and 1 Mpc, size structure should not be erased, which is plotted from left to right. 100 kpc corresponds to typical galaxy size structure. Upper region of thick solid line is excluded by ^{6}Li overproduction by the Catalyzed BBN of the bound-state effect [26,30–34]. Notice that the constraint from CBBN does not depend on the CHAMP mass. We also show the constraint from BBN and CMB spectrum with the mass of CHAMPs being fixed. These constraints should be interpreted with some care in this figure since the mass is fixed independently of the requirement of Eq. (11) for these cases. Upper region of thin solid line is excluded by the BBN constraints from an minimal assumption of possible photodissociation for the visible energy of the decay, $E_{vis} = 10^3$ GeV and 10^6 GeV, respectively. They are obtained by appropriately scaling the result of [17,20]. Upper region of dashed lines are excluded by μ- and y-distortions of CMB spectrum for same visible energies. Their labels are located near the lines. For the case where the lifetime is longer than the age of the Universe, the constraint from the deep sea water may apply, which is shown as the shaded region.

decay of X^- as $E_{vis} = 10^3$ GeV and 10^6 GeV. The lines of the constraints from the photodissociation and the CMB are obtained by appropriately scaling the result of [17,20] and [56], respectively. In addition, here we have assumed that the branching ratio into electromagnetic particles ($B_{vis} \equiv E_{vis}/m_X$) would be the order of unity. The readers can easily obtain these bounds from photodissociation and CMB distortions by scaling the branching ratio into electromagnetic particles correspondingly. When the lifetime of CHAMPs is longer than the age of the Universe, the constraint from the sea water may apply [2–7]. In Fig. 3, we fixed the energy density of CHAMPs to become the same as the present DM density. Thus the constraint from the sea water is $Y_{X^-} < 4 \times 10^{-18}$, which corresponds to $m_X = 10^8$ GeV. As mentioned above, the constraint from large scale structure does not depends on the mass and the yield variable. From the figure, we can see that large scale structure can give the stringent constraint in some parameter regions.

So far we have discussed the case that the dominant component of the nonrelativistic particles in the universe could only be the negative CHAMPs. It would be trivial that long-lived positively-charged particles with $\tau_X \gtrsim 10^{6-8}$ s can be simply excluded by the same reason from the viewpoint of the large-scale structure without taking into account neither the bound-state formation nor their neutralization if they become the dominant component.

[3] It has been discussed that non-thermal production of warm dark matter can also erase the small scale structure by the long free-streaming length due to its relatively large velocity dispersion [43,53].

Furthermore, see also Refs. [54,55] and references therein for another idea to erase small scale structures by introducing bound-state formation through hidden gauge interactions of dark matter. Note that in their models the formation of the bound-state means the kinetic decoupling and the end of the acoustic oscillation of the hidden-charged dark matter. If they considered hidden ^{4}He additionally as well as standard cosmology, their situations might be changed.

5. Summary

In this Letter, we have investigated the evolution of the bound state of CHAMPs with light elements and have shown that the negatively-charged massive particle cannot be neutralized even after its bound-state formation with protons at around 0.5 keV. This is because the charge-exchange reaction by free ^{4}He through $(pX^-) + {}^4\mathrm{He} \to ({}^4\mathrm{He}X^-) + p$ is much more rapid than the cosmic-expansion rate, and almost all X^- will be included into $({}^4\mathrm{He}X^-)$ for $Y_{X^-,0} \lesssim 10^{-12}$, which is positively-charged.

This gives a high impact on the formation of the large-scale structure if those charged particles are dominant non-relativistic components of the universe like cold dark matter at the cosmic time $t \gtrsim 10^6$ s. Then any galaxies cannot be formed by the suppression of the density perturbation through the acoustic oscillations. This simply means that the lifetime of the negative CHAMPs should be $\tau_X < 10^6$ s at longest.

As was discussed in the text, future observations of QSO-galaxy strong lens system can probe the structure down to $k_X^{-1} \sim 1$ kpc. Those future observations will reveal the nature of the long-lived CHAMPs. In this Letter, we have presented the result for the case where the abundance of CHAMPs is fixed to be the present-day dark matter density if they are stable. However, it would be interesting to investigate the case of the energy density of CHAMPs being changed, which will be the issue of a separate paper.

Acknowledgements

We would like to thank Kaiki T. Inoue and Masayasu Kamimura for useful discussions. This work is supported in part by PPARC grant PP/D000394/1 (K.K.), and Grant-in-Aid for Scientific research from the Ministry of Education, Science, Sports, and Culture, Japan, No. 19740145 (T.T.) and No. 18071001 (K.K.).

References

[1] A. Kudo, M. Yamaguchi, Phys. Lett. B 516 (2001) 151.
[2] P.F. Smith, J.R.J. Bennett, Nucl. Phys. B 149 (1979) 525.
[3] P.F. Smith, J.R.J. Bennett, G.J. Homer, J.D. Lewin, H.E. Walford, W.A. Smith, Nucl. Phys. B 206 (1982) 333.
[4] T.K. Hemmick, et al., Phys. Rev. D 41 (1990) 2074.
[5] P. Verkerk, G. Grynberg, B. Pichard, M. Spiro, S. Zylberajch, M.E. Goldberg, P. Fayet, Phys. Rev. Lett. 68 (1992) 1116.
[6] T. Yamagata, Y. Takamori, H. Utsunomiya, Phys. Rev. D 47 (1993) 1231.
[7] C. Amsler, et al., Particle Data Group, Phys. Lett. B 667 (2008) 1.
[8] L. Chuzhoy, E.W. Kolb, JCAP 0907 (2009) 014.
[9] M. Dine, A.E. Nelson, Y. Shirman, Phys. Rev. D 51 (1995) 1362.
[10] M. Dine, A.E. Nelson, Y. Nir, Y. Shirman, Phys. Rev. D 53 (1996) 2658.
[11] G.F. Giudice, R. Rattazzi, Phys. Rep. 322 (1999) 419.
[12] J.R. Ellis, J.E. Kim, D.V. Nanopoulos, Phys. Lett. B 145 (1984) 181;
M.Y. Khlopov, A.D. Linde, Phys. Lett. B 138 (1984) 265;
D. Lindley, Astrophys. J. 294 (1985) 1;
J.R. Ellis, D.V. Nanopoulos, S. Sarkar, Nucl. Phys. B 259 (1985) 175;
R. Juszkiewicz, J. Silk, A. Stebbins, Phys. Lett. B 158 (1985) 463;
J.R. Ellis, et al., Nucl. Phys. B 373 (1992) 399.
[13] M.Y. Khlopov, Cosmoparticle Physics, World Scientific, Singapore, 1999, and references therein.
[14] S. Dimopoulos, R. Esmailzadeh, L.J. Hall, G.D. Starkman, Astrophys. J. 330 (1988) 545;
M.H. Reno, D. Seckel, Phys. Rev. D 37 (1988) 3441.
[15] M. Kawasaki, T. Moroi, Prog. Theor. Phys. 93 (1995) 879;
M. Kawasaki, T. Moroi, Astrophys. J. 452 (1995) 506;
E. Holtmann, M. Kawasaki, K. Kohri, T. Moroi, Phys. Rev. D 60 (1999) 023506.
[16] K. Jedamzik, Phys. Rev. Lett. 84 (2000) 3248.
[17] M. Kawasaki, K. Kohri, T. Moroi, Phys. Rev. D 63 (2001) 103502.
[18] K. Kohri, Phys. Rev. D 64 (2001) 043515.
[19] R.H. Cyburt, J.R. Ellis, B.D. Fields, K.A. Olive, Phys. Rev. D 67 (2003) 103521.
[20] M. Kawasaki, K. Kohri, T. Moroi, Phys. Lett. B 625 (2005) 7;
M. Kawasaki, K. Kohri, T. Moroi, Phys. Rev. D 71 (2005) 083502.
[21] J.R. Ellis, K.A. Olive, E. Vangioni, Phys. Lett. B 619 (2005) 30.
[22] K. Jedamzik, Phys. Rev. D 74 (2006) 103509.
[23] R.H. Cyburt, J. Ellis, B.D. Fields, F. Luo, K.A. Olive, V.C. Spanos, arXiv:0907.5003 [astro-ph.CO].
[24] A. De Rujula, S.L. Glashow, U. Sarid, Nucl. Phys. B 333 (1990) 173;
S. Dimopoulos, D. Eichler, R. Esmailzadeh, G.D. Starkman, Phys. Rev. D 41 (1990) 2388;
R.N. Cahn, S.L. Glashow, Science 213 (1981) 607.
[25] D. Fargion, M. Khlopov, C.A. Stephan, Class. Quantum Grav. 23 (2006) 7305.
[26] M. Pospelov, Phys. Rev. Lett. 98 (2007) 231301.
[27] K. Kohri, F. Takayama, Phys. Rev. D 76 (2007) 063507.
[28] M. Kaplinghat, A. Rajaraman, Phys. Rev. D 74 (2006) 103004.
[29] R.H. Cyburt, J.R. Ellis, B.D. Fields, K.A. Olive, V.C. Spanos, JCAP 0611 (2006) 014.
[30] F.D. Steffen, AIP Conf. Proc. 903 (2007) 595, arXiv:hep-ph/0611027.
[31] K. Hamaguchi, T. Hatsuda, M. Kamimura, Y. Kino, T.T. Yanagida, Phys. Lett. B 650 (2007) 268.
[32] M. Kawasaki, K. Kohri, T. Moroi, Phys. Lett. B 649 (2007) 436;
M. Kawasaki, K. Kohri, T. Moroi, A. Yotsuyanagi, Phys. Rev. D 78 (2008) 065011.
[33] C. Bird, K. Koopmans, M. Pospelov, arXiv:hep-ph/0703096.
[34] J. Pradler, F.D. Steffen, Phys. Lett. B 648 (2007) 224;
J. Pradler, F.D. Steffen, Phys. Lett. B 666 (2008) 181;
J. Pradler, F.D. Steffen, Nucl. Phys. B 809 (2009) 318.
[35] T. Jittoh, et al., Phys. Rev. D 76 (2007) 125023;
T. Jittoh, et al., Phys. Rev. D 78 (2008) 055007.
[36] K. Jedamzik, arXiv:0707.2070 [astro-ph];
K. Jedamzik, arXiv:0710.5153 [hep-ph].
[37] M. Kusakabe, et al., Phys. Rev. D 76 (2007) 121302.
[38] M. Pospelov, arXiv:0712.0647 [hep-ph];
M. Pospelov, M. Pospelov, J. Pradler, F.D. Steffen, JCAP 0811 (2008) 020.
[39] S. Bailly, K. Jedamzik, G. Moultaka, arXiv:0812.0788 [hep-ph];
S. Bailly, K. Jedamzik, G. Moultaka, S. Bailly, K.Y. Choi, K. Jedamzik, L. Roszkowski, JHEP 0905 (2009) 103.
[40] S. Kasuya, F. Takahashi, JCAP 0711 (2007) 019;
F. Takayama, arXiv:0704.2785 [hep-ph];
N. Okada, O. Seto, arXiv:0710.0449 [hep-ph];
J. Kersten, K. Schmidt-Hoberg, arXiv:0710.4528 [hep-ph];
E.J. Chun, et al., JHEP 0803 (2008) 061;
M. Ratz, K. Schmidt-Hoberg, M.W. Winkler, JCAP 0810 (2008) 026;
A. Freitas, F.D. Steffen, N. Tajuddin, D. Wyler, arXiv:0904.3218 [hep-ph];
A. Freitas, F.D. Steffen, N. Tajuddin, D. Wyler, arXiv:0909.3293 [hep-ph].
[41] K. Sigurdson, M. Kamionkowski, Phys. Rev. Lett. 92 (2004) 171302.
[42] S. Profumo, K. Sigurdson, P. Ullio, M. Kamionkowski, Phys. Rev. D 71 (2005) 023518.
[43] J. Hisano, K.T. Inoue, T. Takahashi, Phys. Lett. B 643 (2006) 141.
[44] M. Kamimura, Y. Kino, E. Hiyama, arXiv:0809.4772 [nucl-th].
[45] J. Pradler, arXiv:0909.3429 [hep-ph].
[46] A.A. Klypin, A.V. Kravtsov, O. Valenzuela, F. Prada, Astrophys. J. 522 (1999) 82;
A.R. Zentner, J.S. Bullock, Astrophys. J. 598 (2003) 49.
[47] B. Moore, Nature 370 (1994) 629;
R.A. Flores, J.R. Primack, Astrophys. J. 427 (1994) L1;
J.J. Binney, N.W. Evans, Mon. Not. Roy. Astron. Soc. 327 (2001) L27;
A.R. Zentner, J.S. Bullock, Phys. Rev. D 66 (2002) 043003;
J.D. Simon, A.D. Bolatto, A. Leroy, L. Blitz, E.L. Gates, Astrophys. J. 621 (2005) 757.
[48] J.F. Navarro, C.S. Frenk, S.D.M. White, Astrophys. J. 462 (1996) 563, arXiv:astro-ph/9508025.
[49] B. Moore, S. Ghigna, F. Governato, G. Lake, T.R. Quinn, J. Stadel, P. Tozzi, Astrophys. J. 524 (1999) L19.
[50] G. Gilmore, M.I. Wilkinson, R.F.G. Wyse, J.T. Kleyna, A. Koch, N.W. Evans, E.K. Grebel, Astrophys. J. 663 (2007) 948, arXiv:astro-ph/0703308.
[51] A.V. Kravtsov, arXiv:0906.3295 [astro-ph.CO].
[52] J.R. Primack, arXiv:0909.2247 [astro-ph.CO].
[53] W.B. Lin, D.H. Huang, X. Zhang, R.H. Brandenberger, Phys. Rev. Lett. 86 (2001) 954;
J. Hisano, K. Kohri, M.M. Nojiri, Phys. Lett. B 505 (2001) 169;
J.A.R. Cembranos, J.L. Feng, A. Rajaraman, F. Takayama, Phys. Rev. Lett. 95 (2005) 181301;
M. Kaplinghat, Phys. Rev. D 72 (2005) 063510.
[54] J.L. Feng, M. Kaplinghat, H. Tu, H.B. Yu, JCAP 0907 (2009) 004, arXiv:0905.3039 [hep-ph].
[55] D.E. Kaplan, G.Z. Krnjaic, K.R. Rehermann, C.M. Wells, arXiv:0909.0753 [hep-ph].
[56] W. Hu, J. Silk, Phys. Rev. Lett. 70 (1993) 2661.